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SLENDER DELTA WINGS FOR FUTURE SUBSONIC COMMERCIAL AIRCRAFT

Martin Lichte

Translation of "Schlanke Delta-Flügel für zukünftige Unterschall-Verkehrsflugzeuge", Flug Revue, No. 2, 1973, pp. 27 - 37

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SLENDER DELTA WINGS FOR FUTURE SUBSONIC COMMERCIAL AIRDRAFT

Martin Lichte*

Introduction /27**

The development and testing of the Concorde has shown that the slender delta wing has a number of properties which make it attractive not only for a purely supersonic aircraft. The very desirable properties of the Concorde also during slow flight were verified during the flight testing. These are primarily based on the unusual type of lift production, as will be explained below. The slender delta wing of the Concorde represents a new tool in the hands of the project engineer which must be considered in the development of future commercial aircraft, according to its special specific properties.

Some attempts to do this have already been published. In 1969, Hawker Siddeley already made public a VTOL commercial aircraft having delta wings, called the HS 133. Lifting engines were installed in the roots of the wings (see Flight International issue of Nov. 24, 1969). The VFW Fokker carried out similar investigations (see Flug Revue + flugwelt, 6/7-72). The result was that such a VTOL aircraft can be lighter and more economical than comparable VTOL aircraft designed in the normal configuration

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*VFW Fokker GMBH.

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(so-called "conventional" configuration" consisting of wings, fuselage, and elevator). The advantage of the slender delta wing for VTOL aircraft is the result of the lowered airframe weight, which is achieved by elimination of the elevator, and because of the clever structural formation of the wing/fuselage complex. As is well known, VTOL designs are especially sensitive to airframe weight change, because these have a much more pronounced effect on the overall balance of the design because of the required installed thrust. Finally, we should mention that the first jet supported VTOL aircraft ever built had delta wings (Ryan X-13 "Vertijet" and Short SC 1).

Even conventional aircraft for purely subsonic use can profit from the delta configuration if there are critical weight problems, as the example of the Avro-Vulcan shows. It is known that the weight problem led to the selection of the delta configuration for this V bomber. The further development of this aircraft (prototype MK 1, MK 2), shown in Figure 1, shows how the characteristic curved wing leading edge developed, beginning with a pure delta profile. This is also typical for the Concorde wing, as shown in Figure 2. The Concorde and the Tupolev Tu-144 are the first commercial aircraft having the delta configuration. Future commercial aircraft development can profit from the pioneering done for these aircraft.

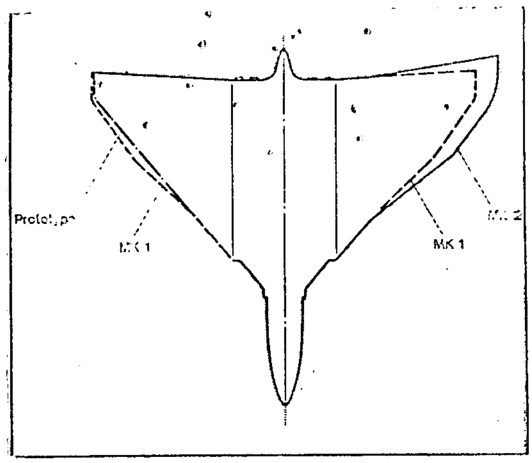

Figure 1. Development of the Vulcan wing

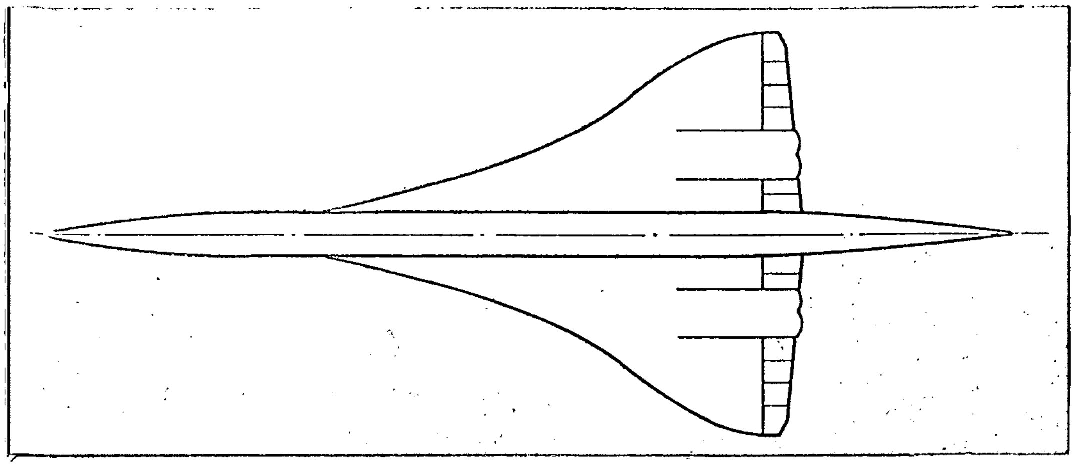

Figure 2. The Concorde wing

Slender Delta Wing Fundamentals for Subsonic Aircraft from the Point of View of the Project Engineer

Aerodynamics

Lift

Flow separation occurs along the wing nose for wings having a small aspect ratio and normal profiles, at relative small angles of attack, and lift coefficients. This is produced by the vortex which occurs there. This vortex extends downstream and corresponds to the edge vortex for normal wings having large aspect ratios. Flow separations are not desirable for "normal" wings, because they reduce the lift production. In the case of slender delta wings, the opposite is true. The separating nose vortex increases in intensity as the angle of attack is increased and produces an underpressure region along the upper surface of the wing, which produces the lift force. Consequently, in the design of the Concorde wing, whis principle of lift production is used. This puts an end to the world-wide opinion, according to which flow separations are dangerous in aircraft aerodynamics, and that they must be suppressed at all costs.

On the contrary, there is a high degree of safety associated with this effect, if one does not suppress the natural inclination of flowing media to separate. Instead, they should be taken advantage of in clever ways, which is done in the case of the Concorde wing. By a suitable shape of the wing nose (sharp leading edge and drawn downwards slightly), separation and vortex formation occur already at the smallest angles of attack, so that there is only one type of flow over the entire angle of attack range, which is found to be exceptionally stable and favorable. There are no sudden changes in the lift behavior or the stability as the angle of attack is increased. It is well known that this does occur for normal swept wings having large aspect ratios. In this case, the changes are produced by local separations.

Because the flow separates continuously, it is not possible to define the stalling of a slender delta wing in the conventional way. Instead it is necessary to define it according to the physics of the lift reducing vortex system:

Already at moderate angles of attack, one observes that the vortices which start at the nose burst far behind the wing at first. As the angle of attack is increased, the position of bursting moves towards the wing trailing edge, but still does not influence the lift increase. It is only after the bursting point reaches the wing trailing edge at very large angles of attack, and even exceeds this point, does the lift decrease. First it decreases slowly, and then much faster. This is why the critical angle of attack for slender delta wings is defined as the angle at which the bursting of the vortices occurs above the wing trailing edge.

This bursting of the vortices just behind the aircraft during flight at large angles of attack (takeoff and landing) is advantageous in practice. As is well known, the edge vortices of large aircraft such as the Boeing 747 extend far behind the aircraft during slow flight and are so intense that the safe distance for following aircraft must be increased. This "spacing" can be reduced because of the bursting of the vortices. This means that more room will be produced in the air space of large airports, which is already overcrowded today.

The flow behavior outlined here for delta wings depends primarily on the wing aspect ratio, i.e., the ratio of the span /28
to average wing chord, as well as on the design of the wing leading edge. The maximum profile thickness only has a small influence. The onset of instability in the sideways motion as the angle of attack is increased depends primarily on the aspect ratio. In the case of very slender delta wings, i.e., those having a small aspect ratio, the flyable maximum lift is considerably limited. Figure 3 shows these relationships in a lucid way. From it one can see that delta wings having an aspect ratio range between 1.2 and 2 can result in lift coefficients around 1, which can be flown. This modest value compared with that of normal wings is compensated for by the very small specific weight (see Figure 4), which makes it possible to use large wing areas or low area loadings.

In the case of normal wings, a reduction in the area loading leads to uncomfortable flying conditions because of increased gust sensitivity. This is primarily due to the magnitude of the lift increase with angle of attack. In the case of the delta wing, this increase is much smaller, especially at small angles

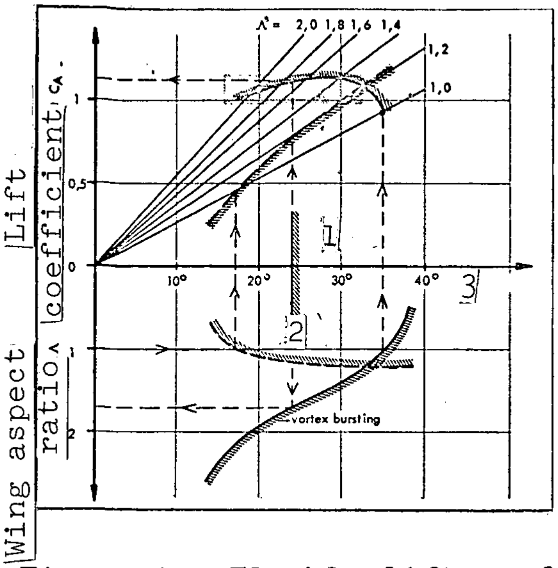

Figure 3. Flyable lift coefficient values for delta wings:

1 — visual limit without tipping nose; 2 — lateral instability; 3 — angle of attack

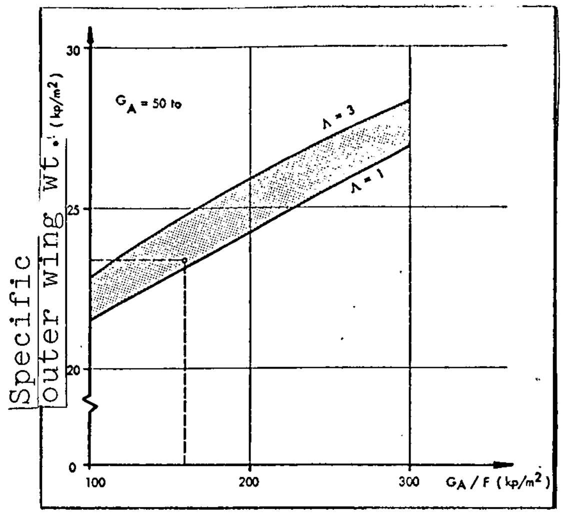

Figure 4. Specific weight of delta wings

of attack, as occur during fast cruise flight. This means that the delta wing, which has a much smaller area loading, will be much more comfortable during flight than conventional aircraft. Figure 5 shows a comparison of the load factor increase by gusts for delta wings and conventional wings. It follows that the delta wing has a smaller gust sensitivity, even for one third of the usual area loading.

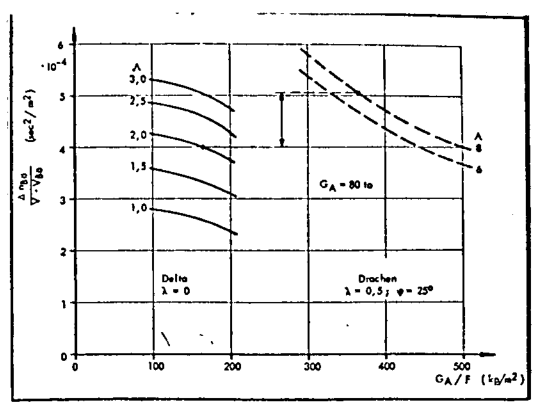

Figure 5. Comparison of the load factors because of gusts

Ground Effect

At first glance, it may seem disadvantageous that the maximum lift of delta wings is only achieved at very high angles of attack between 20° and

30° as shown in Figure 3. This would mean a very long and heavy landing gear for takeoff and landing. However, this is not the case. Delta wings have a very strong ground effect, i.e., increased lift with reduced drag in the vicinity of the ground. Figure 6 shows the lift increase for a typical delta wing when approaching the ground. For example, for a 30 m span and a height of 5 m above the ground (flattening above the airfield), this results in a value of $\Delta c_A \approx 0.6$, so that angles of attack between 12° and 15° are required for touchdown or takeoff. This "air cushion effect" is so strong for large wings, that a flattening occurs automatically during the landing. Consequently, it will be possible for pilots to perform "butter-soft" landing without special skills for steep approach angles, as will be required in future air traffic. Figure 7 shows this situation in parametric form. It is calculated for various approach descent velocities and wing sizes. A maximum value for the descent velocity during landing approach used today is 1000 ft/min, which corresponds approximately to 5 m/sec. The example I shown in Fiture 7 shows that a delta aircraft having a span of 20 m and an initial descent velocity of 5 m/sec, would flatten out at an altitude of about 5.5 m above the ground without any manual intervention. Example II shows that, if the descent velocity during approach is increased to 7 m/sec, it is decreased to zero automatically at a height of about

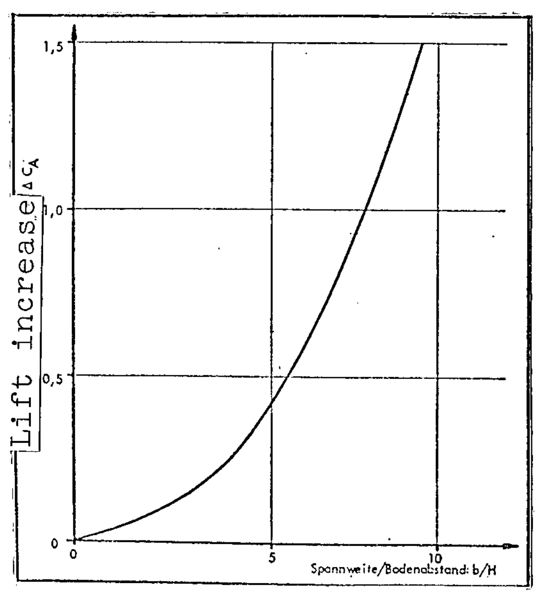

Figure 6. Lift increase in the vicinity of the ground for delta wings

2.5 m above the ground, which is approximately the landing gear height. Example III finally shows the influence of size on this effect. For example, a smaller aircraft having a 10 m span (fighter) and an initial descent velocity of 7 m/sec would drop to 5 m/sec at a height of 1.5 m above the ground (landing gear height). Without any manual intervention, this would result /29 in a crash. The air cushion is thick enough for sufficiently

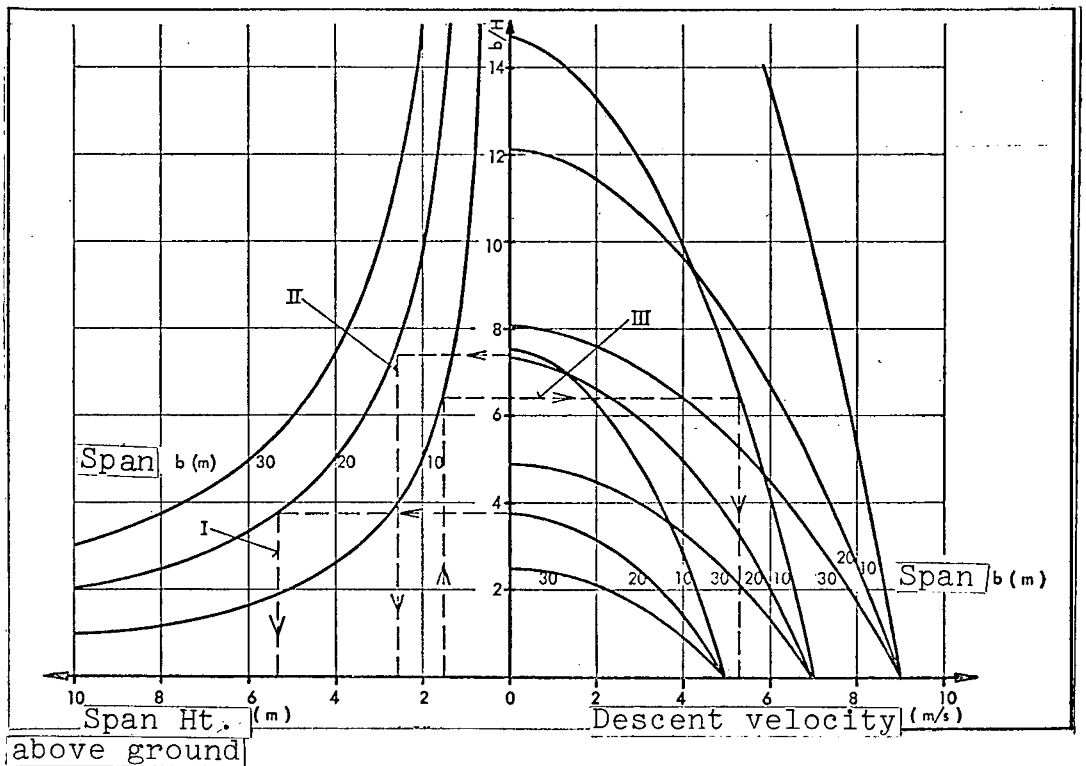

Figure 7. Ground effect for delta wings

large aircraft (transports) in order to aid the landing above the height of the landing gear.

One of the advantages of the delta wing is its insensitivity to side winds during takeoff and landing. This property is amplified by the ground effect because of the "gull" wing position of the wing, which is also characteristic for the

Concorde, and in which there is positive V attitude in the vicinity of the fuselage, and negative V attitude away from the fuselage. Flight experiments have shown that almost no vertical stabilizer deflection is required to control strong side winds.

Drag

The drag of delta wings is quite high for slow flight conditions. It would not make any sense to make a comparison of the drag coefficients, i.e., the drag of conventional aircraft and delta aircraft referred to the area and stagnation pressure, because of the very large differences in area. The lift-to-drag ratio is the quantity which will determine aerodynamic characteristics. The inverse of this value specifies the thrust requirement for the horizontal flight condition based on the flight weight. Figure 8 shows a comparison of lift-to-drag ratio for conventional aircraft and delta aircraft, for which the area loading was assumed to be one third, and the weight was assumed to be 10% less. At first glance, it does not seem that this comparison is very favorable for the delta wing, if we only consider maximum values of the lift-to-drag ratio. In practice, this optimum value is flown very seldom, and only for a short time. This is because the wings are designed for takeoff and landing, and are much too large for fast cruise conditions. This is why very small lift coefficients and lift-to-drag ratios are flown under these conditions which are much smaller than the optimum value. The optimum value can only be flown during holding patterns. For this it is necessary for a delta aircraft to have a larger fuel reserve than conventional aircraft. When flying with a higher specific lift, on the other hand, as occurs during takeoff and landing, the lift-to-drag ratios differ only slightly. Figure 8 gives an example of the landing approach, which can be flown with a conventional aircraft, such as for example, the Boeing 727 at $C_A = 2.8$. For the same approach

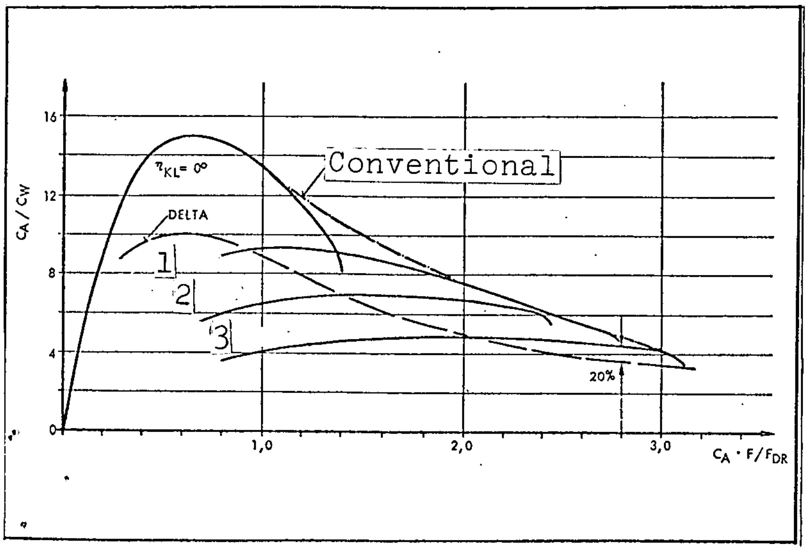

Figure 8. Comparison of gliding ratio for typical delta and conventional aircraft for slow flight, without any influence of Mach number

1 — 15° + forward wing; 2 — 30° + forward wing; — 55° + forward wing

velocity, the delta aircraft has a lift-to-drag ratio which is about 20% less. This means that it has a steeper approach angle, which is not necessarily a disadvantage. For takeoff, on the other hand, we must consider the fact that the delta aircraft is acout 10% lighter, so that this absolute value of the planned engine thrust is about equal to that of the conventional aircraft. The conditions are similar for fast cruise flight. Figure 9 shows the thrust requirement plotted against the cruise velocity at various attitudes. It can be seen that the curves for the delta aircraft and the conventional aircraft (for example, a DC-9) approach each other as the velocity is increased. The absolute thrust requirement for cruise velocities of Mach 0.85 will be about the same. At even higher cruise velocities, the delta wing will clearly be superior.

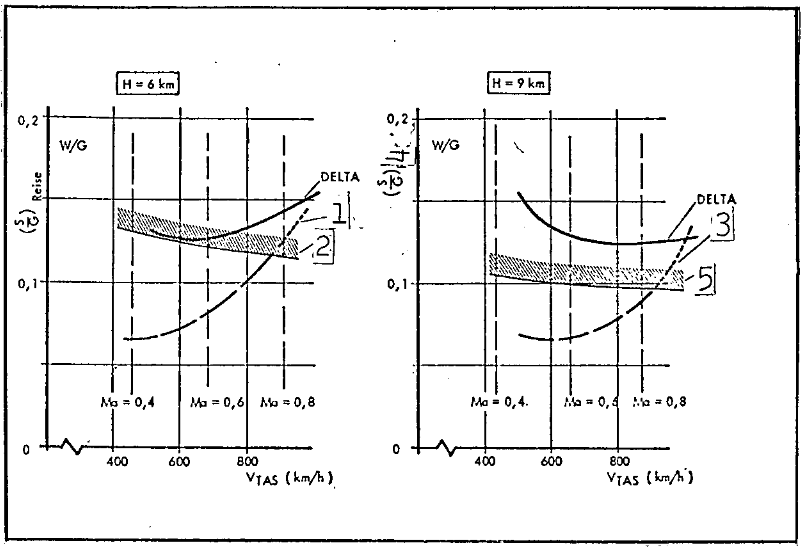

Figure 9. Thrust requirement for cruise flight for delta and conventional configuration:

1 — conventional; 2 — available engine thrust (conventional) 3 — conventional 4 — cruise; 5 — available engine thrust (conventional)

Structure and Weight

In the previous sections, we showed that the delta wing at least does not have any important disadvantages compared with normal wings for high subsonic conditions at which transport and commercial aircraft fly. They even have advantages as far as flight comfort and ground effects are concerned. The most important advantage of the delta wing is its reduced weight, because of the high structural effectiveness of the grate construction which is possible here. This becomes possible for area lifting surfaces. For normal wings, the supporting structure usually consists of a sufficiently stiff box support. The weight of the stiffening members in the direction of flight or perpendicular to the elastic axis of the box (ribs) is relatively small compared with the weights of the upper and lower shell of the box /30 spar, in which very high courses are concentrated. In short aspect ratio delta wings, on the other hand, the relative rib weight increases, because in this case there are substantial bending forces around the transverse axis of the lifting surface. The bending forces around the fuselage axis are much smaller because of the small span than is the case for normal wings. The rib contribution to the wing weight is therefore greater for the delta wing than for normal wings. The spar contribution is drastically reduced. High specific stiffnesses occur because of the relatively smaller profile thickness and relatively large thickness of the delta wings in conjunction with the large profile chord. This also comes about because of the large area moments of the thin-walled cross sections. This means that it is not necessary to use expensive and exotic materials having high elasticity and shear moduli. Quite the contrary, it is possible to have an exceptional stiffness using conventional materials. Because of the improved gust performance, the dimensional loads are smaller, which also reduces the stress level. This is why a delta wing is strong almost automatically. In the case of a normal wing, it is easy for material fatigue to occur because of the high stress level. This is especially true for short range aircraft which have numerous takeoff and landing load cycles. A considerable amount of additional weight must be expended in order to reinforce the wing, and to provide for sufficient strength as a function of time.

The grid grate design of the lifting surface of the delta /35 wing has additional advantages when combined with the usual cylinder fuselage for accepting the payload. This is because the fuselage and wing structure can complement each other and support each other. For this reason, the structural connection of the wing and the body which has been considered as an integral unit here is lighter than would be the case if both parts were dimensioned alone.

In order to make a valid comparison between the delta configuration and the conventional configuration from a structural point of view, the sums of the weights of the wing, elevator (eliminated for a delta wing), landing gear and fuselage weight difference must be compared. We must assume that the basic fuselages are the same for the same payload. Figure 10 shows such a comparison which is plotted against the minimum stagnation

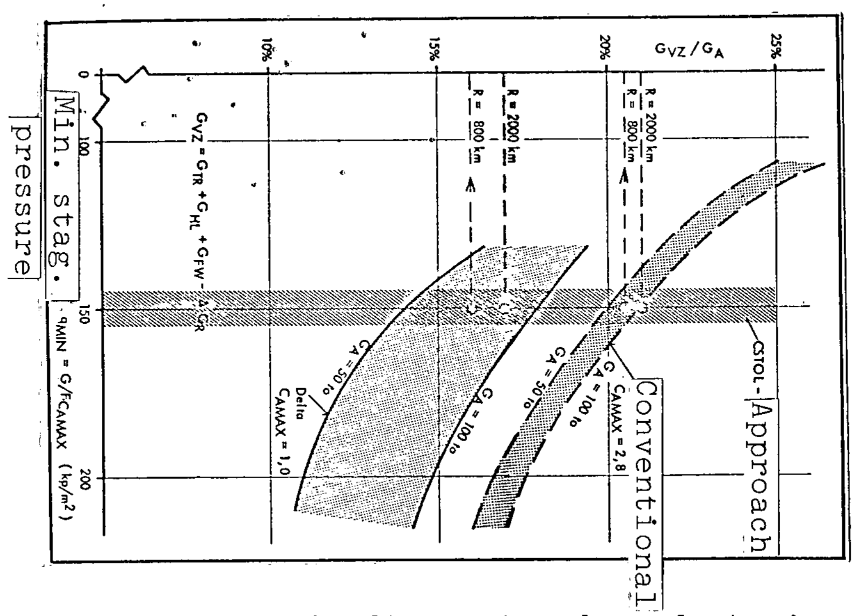

Figure 10. Configuration-dependent airframe fraction G_{VZ}/G_A

pressure. We can see a distinct advantage for the delta configuration which amount to a few percent of the takeoff weight. If possible, additional weights are subtracted because of high fuel reserves or stronger engines; this will work in favor of the payload fraction. "A few percent" seems like "not much", but this is not correct here. We must consider the fact that the economic behavior of aircraft is very sensitive to changes in the maximum payload fraction. As an approximate value, we can say that the direct operational costs are inversely over-proportional to the payload fractions of comparable aircraft. For example, if we assume a maximum fraction of 22% takeoff weight for a short range aircraft and 25% for another aircraft, then the operational costs of the latter will be better by more than 12%. On the other hand, it is known how much technical effort is expended to reduce the operational costs of a comparable aircraft only by a few percent compared with a competing version. Thus a payload factor change of 1% is already very sensational. These changes are achieved without any extremely expensive exotic materials, which would eliminate any cost advantage.

Final Conclusions

Slender delta wing configurations have a number of advantages compared with conventional configurations, even in the subsonic range. The development and testing of the Concorde and Tu-144 show that this flying principle using wings of this type can be used in civilian applications as well. This means that a new tool has been given to the project engineer, which has advantages and disadvantages which should be evaluated carefully.

We can mention the following advantages:

— light structure;
— no stalling is possible;
— natural flattening due to the ground effect;
— insensitive to side winds;
— favorable flight properties;
— insensitive to Mach number;

— no negative fuselage influence on the lift;
— no complicated high lift flap systems are required;
— great stiffness;
— simple structure construction;
— simple manufacture;
— no expensive materials are required;
— remains strong without any additional weight;
— large volumes available in the wings;
— high crash-worthiness;
— small spacing;
— takeoff without rotation loss.

We can mention the following disadvantages:

— higher installed thrust;
— higher fuel reserves for holding pattern flight.

According to this, the application of the delta wing to cases in which at least one of the disadvantages is unimportant seems very promising. This apparently is true for short takeoff applications. For comparable conventional aircraft, a higher installed thrust is needed than for CTOL aircraft in order to obtain a sufficient acceleration or in order to increase the upward lift by actively influencing the wing circulation. This means that the additional expenditure for thrust in the case of a delta configuration can be relatively reduced or even eliminated. In the following, we will describe a short takeoff design in the delta configuration for a future commercial aircraft. We will also compare it with a comparable conventional configuration.

Project Design for a CSTOL Commercial Aircraft Having a Delta Configuration

Definition and Basis of the CSTOL Technology

CSTOL is a modification of the notation STOL for short takeoff capability. It refers to conventional short takeoff and landing. The word conventional means that the short takeoff capability is achieved using conventional means, i.e., by somewhat reduced area loadings in conjunction with flap systems. /36
These flap systems are refined with respect to what is used today, but they are not washed by the engine jets nor does the flow pass through them. Also, additional installed thrust is required in order to achieve sufficient takeoff accelerations. Using this simplified STOL technology, it is possible to operate with runway lengths between 3000 and 4000 ft. These runways are available at almost all locations.

At the beginning, the STOL requirement meant a takeoff distance of 2000 feet in the U.S.A., and the approach angle had to be between 6 and 9°, instead of a maximum of 3° used in conventional air traffic. If we assume a maximum flyable descent velocity of 1000 feet per minute, the approach velocity is about 40 m/sec for an approach angle of 7.5°, which is about half as fast as for aircraft operating today. The stagnation pressure amounts to only about one fourth the values used today, so that the lift coefficients must be larger by a factor of 4 if the area loading is not to be changed. Even if the area loading is reduced, there are many difficulties connected with control and stabilization because the moments of inertia increase, and about the same control accelerations must be produced with one-fourth of the CTOL stagnation pressure. The measures required to control these problems are connected with a great deal of effort, which can already be seen from the corresponding design.

Figure 11 shows two typical designs for the 2000-ft takeoff distance. The large rudders make a first impression. Of course they are very heavy, as are the huge engines for the Lockheed design. These engines are required in order to obtain the high wing lift coefficients by blowing on the flaps. The Boeing/Aeritalia design has four engines in addition to the four forward engines. These are located on pylons. They are used for supplying the air to the high lift flap system (augmentor wing). In addition, we notice the large distance of the control surface unit (notice the relative small length of the cabin, which is apparent from the position of the rear door). Also there are nose flaps at the elevator. All these provisions cost money.

Figure 12 shows the additional expenditure for various capital STOL technologies required to shorten the runway length. This is given in the form of relative operational cost increases compared with the difference between CTOL and VTOL expenditure. We can clearly see the large cost increase below 3000 feet runway length, which reaches the level for vertical takeoff aircraft rapidly and then exceeds it. For this reason, and because of the fact that a considerable improvement in air traffic conditions seems possible if the runway lengths are reduced to 3000 - 4000 feet, almost all aircraft manufacturers have recently redirected their efforts in this direction. This is also because the noise situation has been eliminated because of the new engines, see Figure 13.

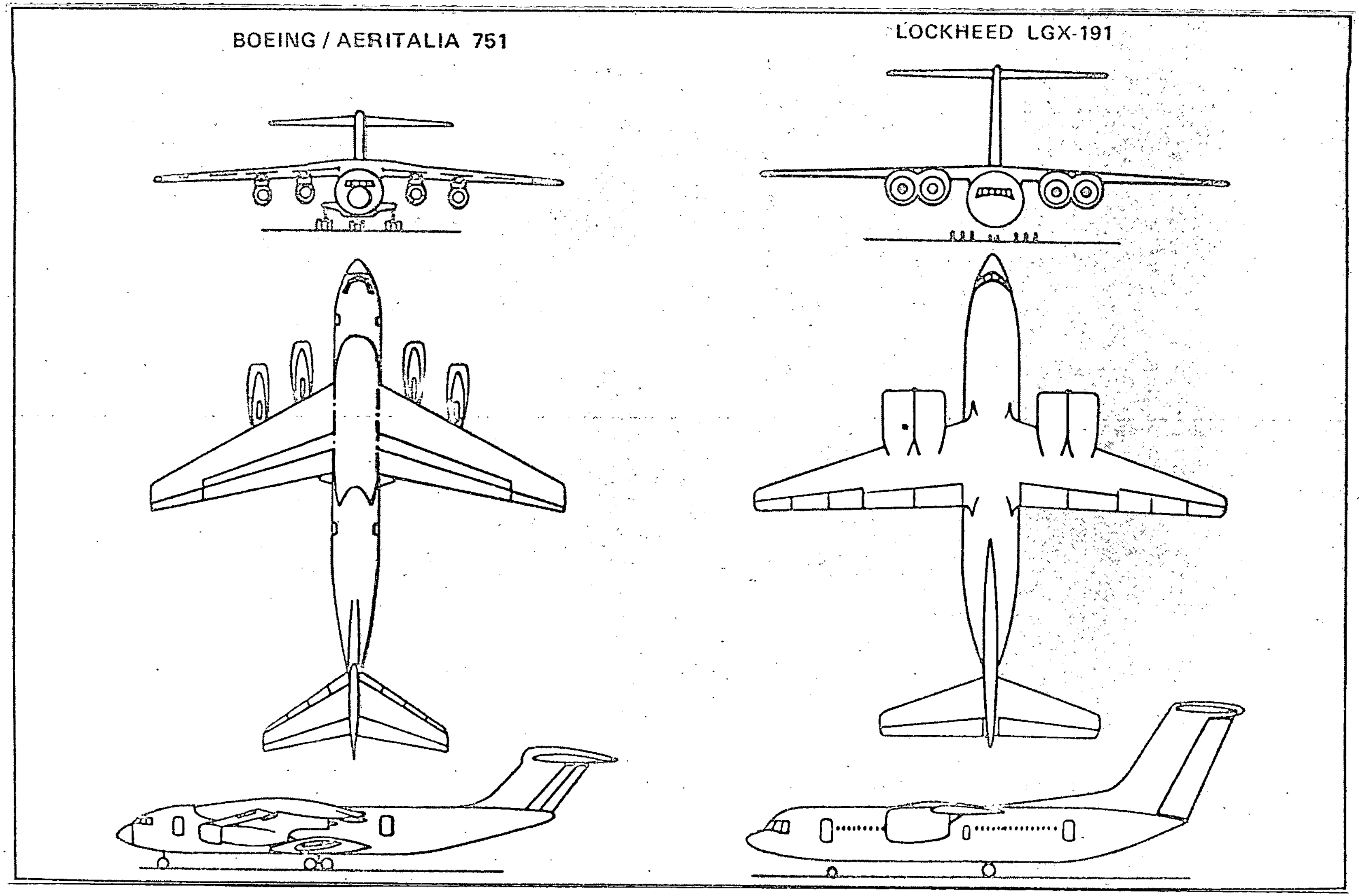

Figure 11. Typical STOL designs for 2000-feet air field

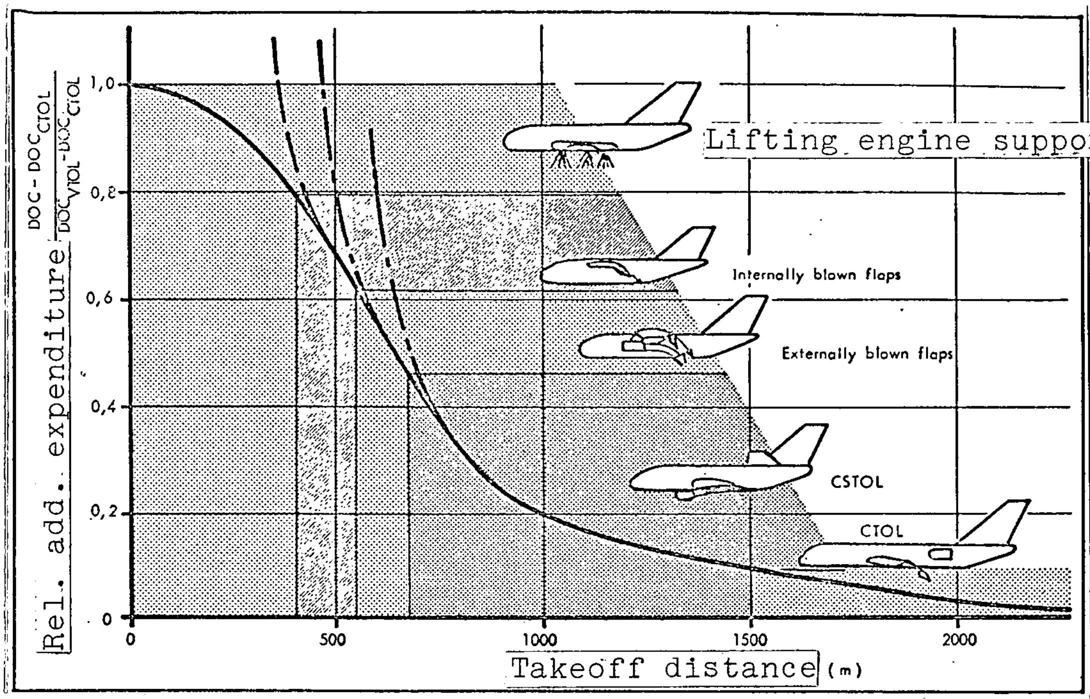

Figure 12. Relative additional expenditure of various STOL technologies

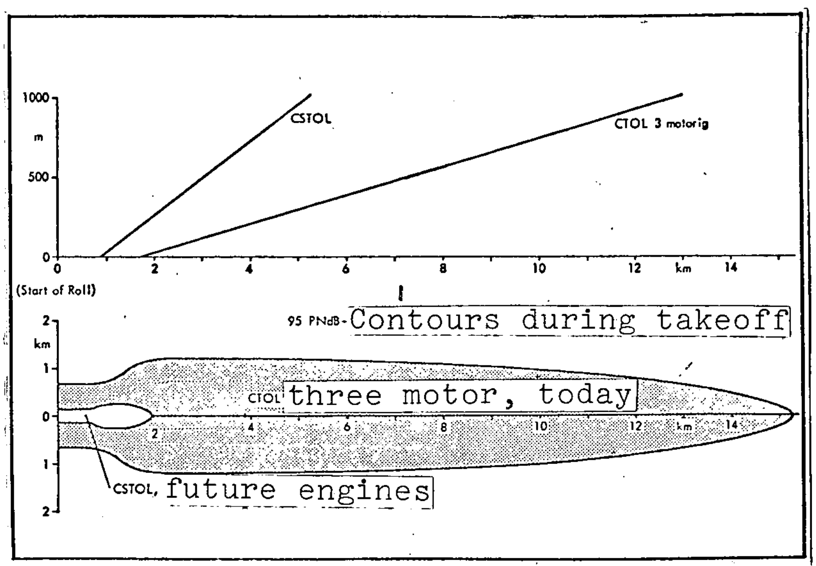

Figure 13. Ground acoustic fields for CTOL and SCTOL

Design of a CSTOL Delta Aircraft

The usual designs for obtaining CSTOL capability follow the direction of high lift coefficients using complicated flap systems in conjunction with reduced area loading and higher installed thrust. These methods are known in principle. The delta aircraft, on the other hand, represents an alternative which has been overlooked up to the present, but which is characterized by its enormous simplicity. Figure 14 shows how this principle can be ordered among the known principles. We should note that a modern delta aircraft cannot be stalled in the conventional way, so that the velocities shown in Figure 14 can really be flown by a delta aircraft. For the other technologies, it is necessary for them to have certain separation distance with respect to stalling conditions.

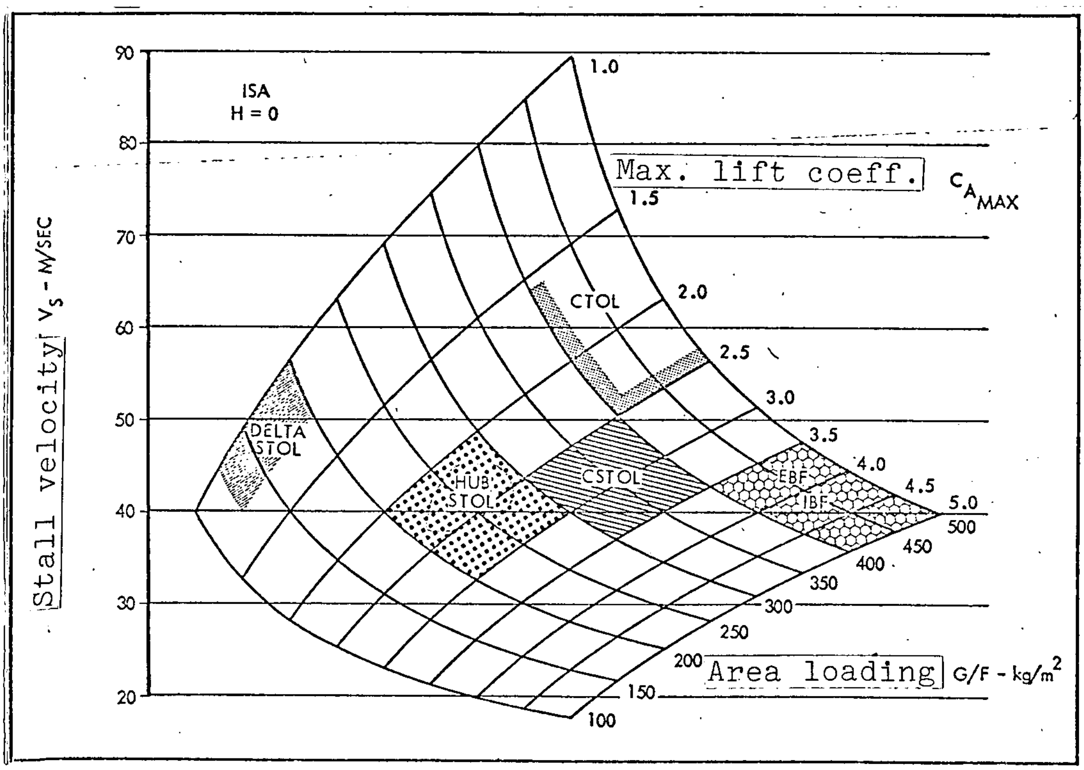

Figure 14. Influence of the aerodynamic design on the stall velocity

In the following, we will describe some aspects for the design of a CSTOL aircraft having the delta configuration for 169 passengers and 1.5 tons of freight. This is shown in Figure 15. The short landing capability of this aircraft on airports having a length between 3000 - 4000 feet (1000 to 1250 m) was decisive for selecting the area loading of about 175 kp/m^2. Even when we fly this aircraft with the same degree of safety with respect to C_{Amax}, as is done for conventional aircraft, we obtain an approach angle of more than 6°, considering the possible increased descent velocity of 7 m/sec. The small lift-to-drag ratio of the delta wing has a decisively favorable effect for short takeoff. Touchdown is obtained by removing the engine thrust with a subsequent delay by the drag, which can be increased by corresponding spoilers. This means that the touchdown velocity is about 50 m/sec. The braking is performed with an average deceleration of about 0.35 g, so that only one-third of the runway is required for braking.

The takeoff conditions dimension the installed engine thrust. They are designed by the so-called second segment (stationary ascent with one engine failure) as detailed investigations have shown. In the case of normal aircraft, this is not the case because the requirement for a sufficient acceleration in the case of engine failure dominates here, after the so-called "critical point". This point of the takeoff trajectory (which depends on the aircraft) is defined as the point along the trajectory which, when passed, will still require the takeoff process to be continued even if one engine has failed, because /37
a braking to the end of the runway is no longer possible. Figure 16 shows the required CSTOL installed thrust for conventional aircraft as a function of the number of engines. For a four-engine aircraft, we obtain a value of 0.43, which is quite large compared with conventional takeoff aircraft (0.25 - 0.3). The

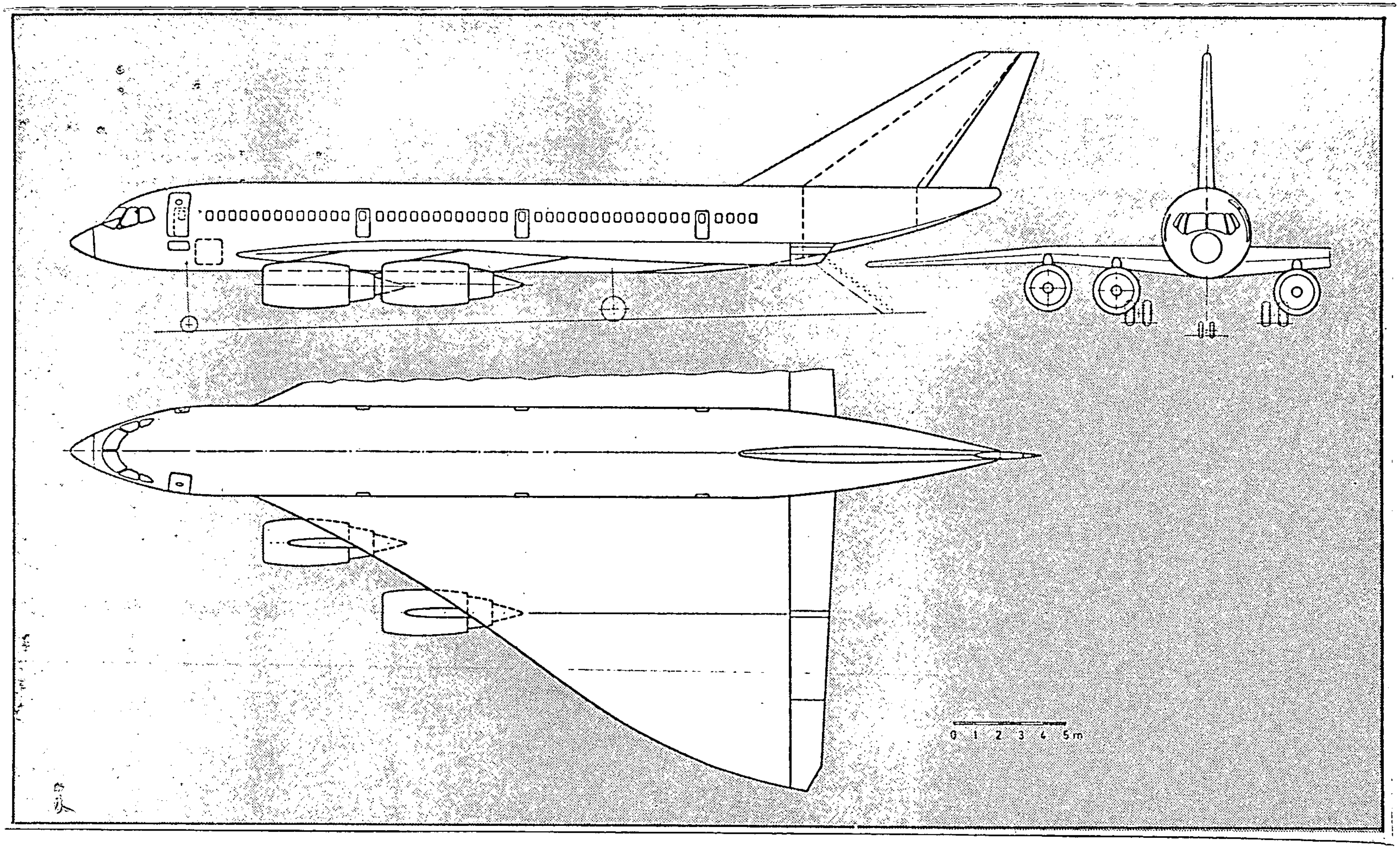

Figure 15. The delta STOL configuration

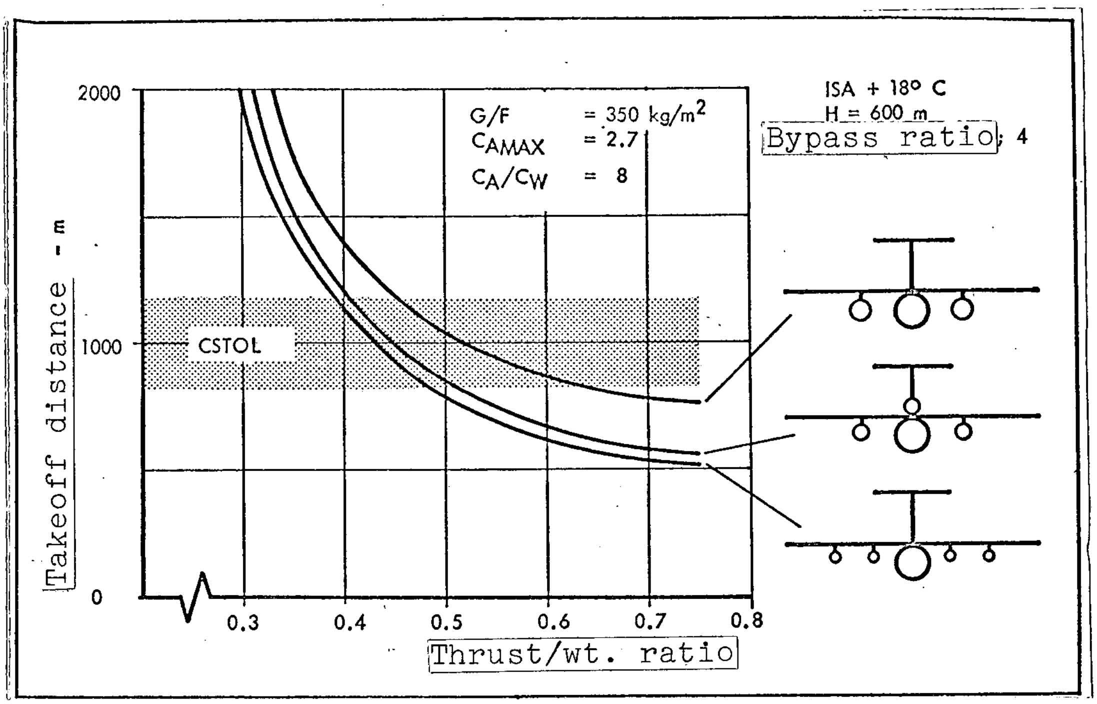

Figure 16. Thrust requirement for conventional CSTOL aircraft

most important disadvantage of the delta configuration, the relatively installed thrust, can be removed if it becomes possible to accept an installed thrust of 0.43.

Figure 17 is a diagram which shows that for an aspect ratio of 2, it is possible to accept the same installed thrust. Since the delta wing will certainly be lighter than a comparable conventional aircraft, the absolute thrust requirement will be even smaller in this case. This means that it is possible to design a three-jet delta aircraft which will have no disadvantage as far as the engine costs are concerned with a CSTOL conventional aircraft. The direct operating costs are decisive in the final analysis. These will show the advantages and disadvantages of various concepts in their proper perspective.

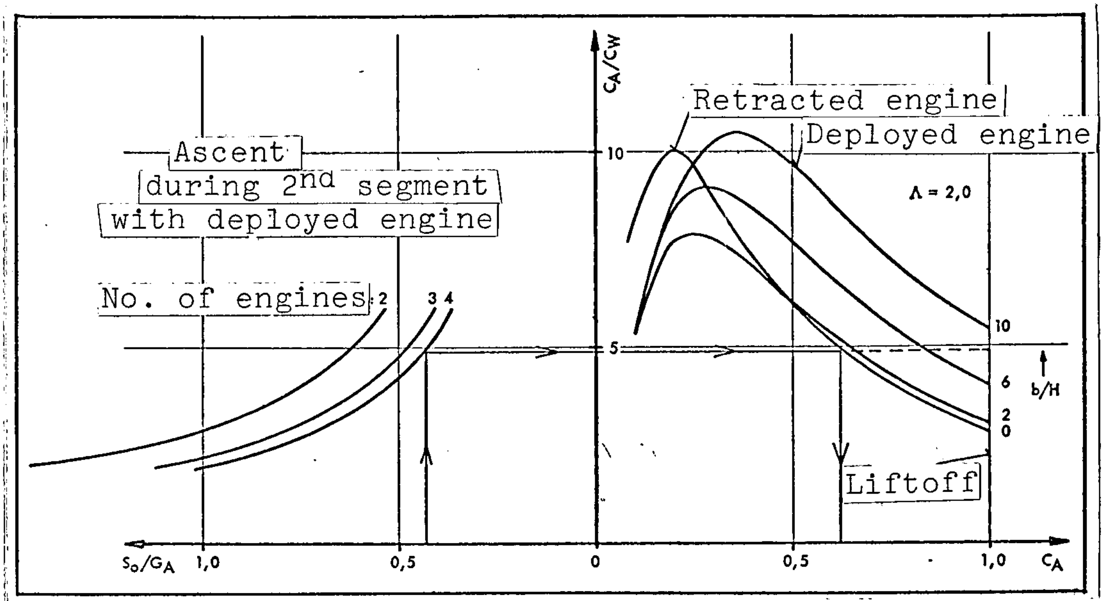

Figure 17. Thrust requirement and aerodynamic characteristics for the second takeoff segment of a delta aircraft

Figure 18 gives such a comparison in parametric form for two different takeoff distances. The upper half of the diagram shows the relative additional costs of delta configuration and conventional configuration compared with a horizontal takeoff conventional aircraft. Depending on takeoff distance, the advantage amounts to 4 - 10% in favor of the delta configuration. Very careful assumptions were made; for example, doubled fuel reserves were assumed for the delta aircraft. The lower half of the diagram can be interpreted to determine the very important payload factor. The installed thrust and the airframe fraction G_{VZ} which depend on the configuration are important. The latter is shown in Figure 10 as a function of the minimum stagnation pressure and aircraft size for both the conventional and delta configurations.

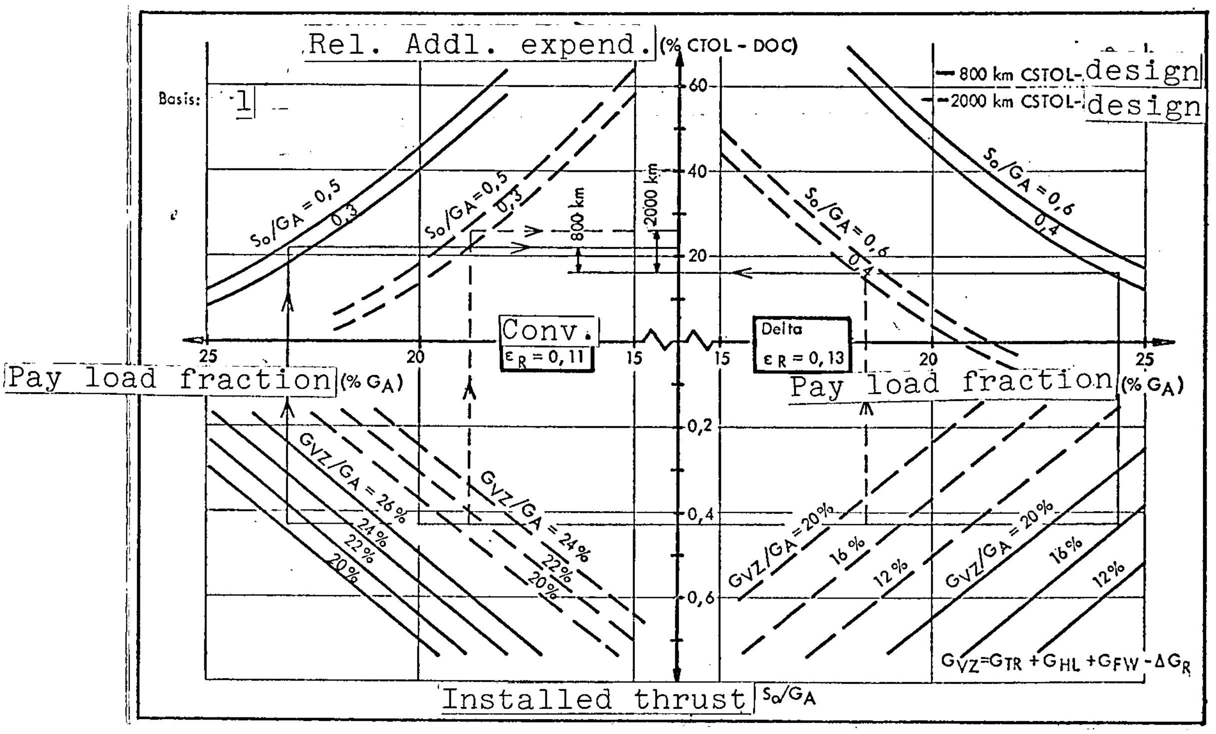

Figure 18. CSTOL technology cost comparison: Conventional/delta configuration

1 — CTOL conventional aircraft with $S/G = 0.25$; $\varepsilon = 0.10$; $G_N/G_A = 22 - 26\%$

Final Conclusions and Look into the Future

Using relatively simple ideas, we were able to show that the delta configuration is especially well suited for CSTOL applications. This is because the required installed thrust is not higher than for a comparable conventional aircraft configuration. The installed thrust is used well during all phases of flight. The structural advantage of the delta configuration results in a lighter aircraft, in spite of the doubled fuel reserves for hold pattern flight. This is especially apparent in the direct operational costs. Usually an enormous amount of technical complexity is required in order to obtain a few percent advantage in operational costs. In the casesof the delta configuration for CSTOL application, the opposite is true. This is because technically it is a very simple device without any complicated flap systems.

Another advantage which has not been mentioned has to do with the development potential. A subsequent "stretching" of the aircraft, which has been done in the case of horizontal takeoff aircraft in order to adjust to changing market conditions, is not so simple for CSTOL aircraft, if the takeoff and landing performances are to be retained. If addition to an increased installed thrust, it is necessary to increase the size of the wing. In the case of the delta configuration, it is possible to install flat lifting engines, for which there is ample free space in the wing roots. There are no complicated and disadvantageous jet influences on the elevators, such as occur for the conventional configurations. In this way, it also seems possible to develop a device which can be continuously developed in the direction of VTOL.